On Grandmother Neurons and Grandfather Clocks

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ABSTRACT—What does contemporary neuroscience offer educational practice? The promise seems immense, as we come to understand better how the brain learns. However, critics caution that only a few concrete implications for practice have emerged, nowhere near a rewrite of the craft of teaching and learning. How then can we understand better the relationship between neuroscience and educational practice? It is argued here that to speak to the classroom neuroscience has to shout across two gaps. The first and most familiar are different levels of explanation. The second concerns the epistemological contrast between explanation theories and action theories, roughly the contrast between basic science on the one hand and engineering science and craft on the other. Just as we do not expect Newton's laws in their fundamental generality to deliver specific designs for pocket watches and grandfather clocks, neither should we expect fundamental neuroscience to radically redesign particular practices of teaching and learning grounded in educational research and experience.

GRANDFATHER CLOCKS

Once upon a time, clockmakers were considered wondrously wise. The levers, the weights, the springs, the gears that they configured into timepieces from pocket watches to grandfather clocks amazed everyone. Clockmakers seemed to have mastered the science of time.

Then the developments of Isaac Newton in physics gave rise to a group of scholars committed to understanding nature at a more basic level. When they turned to matters as mundane as clocks at all, some of them said, "Clocks are simply elaborate expressions of Newtonian principles. To understand clocks deeply, and to construct them better, we need to seek the science of time in its fundamental physical foundations." So the debate raged: Were the secrets of time to be found in the richly developed craft of the clockmakers or the deep science of the Newtonians?

This little story has in it far more of parable than of history. The parable is a way of probing the complicated relationship between education and neuroscience. It was inspired by my participation in the October 6–8, 2004 *Conference on Building Usable Knowledge in Mind, Brain, and Education* at the Harvard Graduate School of Education, a conference replete with both educational ideas and findings from cognitive neuroscience.

In our parable, the educators, including designers of education and researchers on educational practice, are the clockmakers. Neuroscientists plumbing the fundamental nature of cognition and learning are the Newtonians. And the basic question is very much the same: Are the secrets of teaching and learning to be found in the developed and empirically grounded craft of educators and educational psychologists or in the gradually emerging insights of neuroscience?

The neuroscientists certainly can assert that what is going on in education *has* to reflect the workings of the brain. Accordingly, understanding the brain better could inform powerfully how we manage teaching and learning. The popularity of "brain-based" education is testimony that many others find such a stance natural. Moreover, one thing for sure about education: It does not function like clockwork. More basic insights about how to educate well would be most welcome. On the other hand, what neuroscience so far has had to offer education is distinctly meager (e.g., Bruer, 1997, 2004). Often, what gets advanced in the name of "brain-based education" is not brain based at all in any reasonable sense but mind based—grounded in well-established principles of psychology with not a neuron in sight.

The goal here is certainly not to argue that neuroscience is mute in the classroom but rather to elucidate why neuroscience, to speak to the classroom, has to shout across a gap—in fact, two of them. The first and most familiar of these gaps fall between different levels of explanation. The second and less familiar concern the epistemic differences between explanation theories and action theories, roughly

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the difference between basic science on the one hand and engineering science and craft on the other.

GRANDMOTHER NEURONS

Today, the notion of grandmother neurons seems as old-fashioned as mint juleps. Originally, some scientists thought that the brain encoded concepts in individual neurons. When you saw your grandmother, after a lot of complicated preprocessing a particular "grandmother neuron" would fire, completing your identification of the lady. Sometime in the course of your early development, this neuron had come to stand for your grandmother.

Today's neuroscientists dismiss this idea. Your grandmother and other concepts are represented in distributed ways in the brain, not at single loci. Nonetheless, the idea of a grandmother neuron provides a convenient symbol for the quest to understand complex macrophenomena (like recognizing grandmothers) in terms of the structures and dynamics of the brain (the grandmother neuron or at least some grandmother-related pattern of neural activation).

Levels of explanation pose one challenge to this endeavor. Discovering a grandmother neuron would illuminate how the brain works, but it would not tell us that much about who grandmothers are or how to love and respect them. If we also found neurons for love and respect firing in consort with the grandmother neuron, we would then know more about the brain but still no more about family life. Everyday concepts like grandmother and also many technical concepts from psychology describe our mental workings at a functional level conceptually independent of how they are implemented in the brain (Bruer, 1997, 2004). Discovering what is happening in the brain usually simply adds a level of analysis interesting in itself but not that illuminating about the story at the functional level.

The turf war between the Newtonians and the clockmakers underscores the nature of the dilemma. To be sure, basic physical laws govern everything a clock does. At the same time, most of what makes a clock work like a clock lies in the functional relationships of macrostructures like gears and levers configured in just the right pattern to achieve the targeted result. The physical laws cherished by the Newtonians constrain strongly how a clock might work, but tell us very little about its functional architecture.

This does not mean that a more physical level of analysis never has lessons for a more functional level. For instance, the Newtonians would know what the clockmakers probably would not: The period of a pendulum depends on the acceleration of gravity. The grandfather clock would not keep good time on the moon. Likewise, certainly studies of the brain might help to explain malfunctions and reveal unexpected limits and strengths of thinking and learning. It is described later on this article.

WHAT CLOCKMAKERS WANT

There is a second gap between neuroscience and the functional phenomena important to teaching and learning—not a matter of contrasting levels but a matter of contrasting epistemological agendas. Here, it is useful to draw a distinction between *explanation theories* and *action theories*. Explanation theories aim to account for how some piece of the world works—the thinking and learning the brain does, the time keeping a clock does. The neuroscientists and the Newtonians are both after fundamental explanations: they both want to know what makes the clocks of the universe tick.

Action theories guide getting something done. They might concern the design of a reading program or a grandfather clock. Action theories are not just recipes. They are principled and somewhat general, but in a heuristic action-oriented way. The educators want principles for getting reading or calculus learned well, and the clockmakers want principles for designing and building good clocks.

The craft of teaching and learning involves a number of action theories well-backed by psychological research. To mention a few that will come up later (Petitto & Dunbar, 2004; Rose, 2004; Rose & Dalton, 2009), just-in-time informative feedback is tremendously important. Often, the development of a practice benefits from modeling and scaffolding the practice and then fading the support as the learner becomes able to take charge. Conceptual change can sometimes be induced by guiding learners to encounter and puzzle over data discrepant with their early conceptions—but with a caveat: in many cases their early conceptions remerge under new conditions or after some time has passed.

From an epistemological standpoint, explanation theories and action theories are rather different. They involve distinctive "epistemic games," contrasting paradigms of describing, explaining, and justifying (Perkins, 1997). Explanation theories reach for fundamental principles with very broad applicability. It is good when an explanation theory is as much about planetary systems as clocks. Action theories, in contrast, need specificity and focus to inform practical action.

Explanation theories typically strip away complications such as air resistance to get at underlying principles. Action theories, in contrast, are like engineering guidelines: They need to take account of the messy aspects to help get something practical done in the world. Indeed, properly fleshed-out versions of just-in-time feedback or scaffolding and fading or inducing conceptual change with discrepant data involve considerable elaboration of the craft.

As to justification, explanation theories are claims about the world, true or false, and subject to disconfirmation in the Popperian tradition. Action theories are less claim-like and more tool-like. Their test is the test of practical efficacy. When an action theory works well here but not there, we do not call it false; however, we call a Philips head screwdriver false

when it does not work well on an ordinary screw. We simply understand its range of application better and keep it around for the good turns it can do where it can do them.

Besides neuroscience and educational science, there are many familiar cases of explanation theories juxtaposed with action theories. Basic physics keeps bridges up but has little to say about the craft of building particular kinds of bridges. Basic biological science stands behind medical practice and points in suggestive directions without telling us just what to do about polio or AIDS. Computer scientists who prove that a particular sort of result is computable with certain resources are not likely to be the ones who write the programs to do it, a whole craft in itself.

The moral for the turf war between the Newtonians and clockmakers, or between the neuroscientists and the educators, should be clear. They are not actually battling for the same turf. The focus of the two enterprises is quite different, explanation theories versus action theories. We should not expect either one to speak to the other in a thorough way.

In part, the turf war surely reflects issues of prestige. Engineering science tends to be seen as playing second fiddle to basic science, with its fundamental reach. We admire Edison for his inventiveness, but we revere Einstein for his insight. However, from a distanced perspective of social, economic, and intellectual development, it is far from clear which fiddle plays best, or even whether that is a very good question. Much of society's progress plainly depends on engineering science. Often the engineering science predates considerably the basic science, which plays catch-up. Thus, the making of Japanese swords attained impressive sophistication centuries earlier than modern metallurgy. To be sure, often the basic science feeds the engineering science, as with the development of the laser. On the other hand, engineering science commonly enables the construction of instrumentation leading to discoveries in basic science.

Plainly explanation theories and action theories sustain a complex symbiotic relationship. It makes more sense to respect both for what they are and foster their generative interactions than it does to establish a pecking order.

WHAT NEURONS SAY

A number of papers presented at the October, 2004 conference and included in this special series illustrate in interesting ways the double gap between neuroscience and good practices of teaching and learning—different levels of explanation on the one hand and explanation versus action theories on the other. For example, Rose (Rose, 2004; Rose & Dalton, 2009) begins his treatment of struggling readers with a perspective from neuroscience on the process and challenges of reading. The process is highly distributed in the neural system. Different brain regions and architectures account for the pattern recognition involved, strategic self-management of the reading process, and affective and motivational factors. For instance, perceptual deficits such as blindness and deafness impact on pattern recognition, and problems such as attention deficit hyperactivity disorder and Asperger's syndrome undermine strategic self-management.

Conventional print media serve mainstream students well enough but offer little support to the range of challenges encountered by struggling readers. Rose shows how today's technology can provide more powerful learning environments flexibly adaptable to different sorts of readers. Text can talk, fonts can become large, definitions can pop up with the click of a mouse. Text environments can include models of a skill or strategy and scaffold practice with just-in-time feedback and a gradual withdrawal of support over time as skill develops. Rose and his colleagues not only have developed such environments but extensively tested them, demonstrating impressive impact on comprehension, follow-up class discussion, and later performance on standardized reading tests.

All this represents a coherent grounded approach to the problems of struggling readers . . . and a provocative example of the double gap. The neuroscientific account extends our understanding of difficulties of pattern recognition, strategic self-management, and motivation to the neural level, but by and large does not revise our picture of the macrophenomena (level of explanation gap). Furthermore, the explanatory picture of the reading brain does not connect directly to the practices embedded in the innovative reading environment (explanation theory/action theory gap). To expand on the latter, Rose himself emphasizes that modeling, scaffolding, withdrawal of support, and so forth are powerful moves found across many settings of learning. As noted earlier, they are action theories grounded both in experience and in a range of psychological and educational research as diverse as cognitive-developmental frameworks and behaviorism. This does not mean that the neuroscience has no relevance to the educative approach: Rose uses it nicely as a way of mapping the nature and diversity of the problems to be addressed and as a basis for organizing his toolkit of action theories. It is no criticism of the considerable achievement to say that the double gap is in clear view even though crossed by a footbridge or two.

Petitto and Dunbar (2004) present other contributions to learning theory and educational design that make the double gap salient. Their offering begins with a debate concerning bilingualism: When a child learns two languages, do they interfere with one another? The authors report a series of findings demonstrating that children can learn two languages without interference quite readily, simultaneously, or with the second language somewhat delayed but following essentially the same phases of development at the same pace. However, the second language needs to be richly engaged, not just in

classrooms but in various other facets of life, for mastery of it to match the first language.

These are important results for the highly politicized issue of bilingual education. They carry clear action recommendations, such as striving to provide varied learning environments for second language learners. However, although characterized as findings from cognitive neuroscience, they are essentially descriptive rather than explanatory. They deal with juxtaposed action theories, gauging the impact of various timing conditions on mastery of two languages. They do not depend on any particular model at the neural level or indeed at the psychological level.

The second part turns unambiguously to the brain, describing functional magnetic resonance imaging (fMRI) studies of brain activation as college students, some well-versed in physics and some not, observed phenomena consistent with naïve theories of motion or with Newtonian theories. An intriguing and important pattern of results emerged. The fMRI observations suggest that students' brains actively inhibit data discrepant with their preferred theories. This throws into question the power of a typical constructivist action theory mentioned earlier. This throws into question the power of a typical constructivist action theory mentioned earlier, namely the theory that revealing to learners anomalies in their naïve conceptions can induce conceptual change. Moreover, the fMRI observations suggest that students well-versed in physics, who do display a Newtonian conception of motion, have not forgotten their naïve theories but suppressed them. This offers evidence against the psychological theory that the new conception, once stably adopted, entirely displaces the old one. It also helps to explain why backsliding to previously held naïve theories is so common; the naïve theories are still present.

In contrast with the bilingualism case, here we certainly have an interesting explanatory theory at a brain level. However, the findings more corroborate psychological and educational concerns than they radically rewrite the action theories of constructivist educational practice. For one point, many students do successfully learn these difficult concepts, arguing that sometimes the anomaly approach works. The idea that new learning overlays rather than displaces old learning is suggested by a number of psychological, not just neurological, phenomena. Finally, both empirical and explanatory challenges have been raised for a long time about anomalous data as an adequate driver of conceptual change, without any reference to brain function (e.g., Strike & Posner, 1985).

FROM BRAIN TO MIND

So far I have framed this argument in terms of neuroscience. It actually applies somewhat more broadly. Never mind the brain, consider the mind. Aspects of hardcore cognitive psychology that deal with attention, perceptual search, and such matters are also likely to show the two gaps. They may help to explain the black-box operating characteristics of some aspect of learning, but without leading to revisions of those black-box operating characteristics, which are the basis for practices of teaching and learning. Other psychological investigations address phenomena closer to the level of the classroom, but with an emphasis on explanation theories accompanied by hints of corresponding action.

For example, Spelke (2004) offers an intriguing account of the development of number, emphasizing how much of fundamental importance happens before a child ever walks into a classroom. Two different systems for handling numbers appear even before language. Infants can perceive the exact cardinality of very small numbers of objects as well as track the impact of adding or subtracting single objects. Also, infants can perceive the contrast between larger cardinalities when the ratio is great enough, for instance, seeing that there are more objects in a set of eight than in a set of four, without encoding exactly how many there are in either. Still before any formal instruction, language mediates the construction of relationships between these two systems, yielding the rudiments of the natural number system, with its notion that every finite set, however large, has an exact cardinality, that shuffling the set does not change its cardinality but adding or subtracting the set does.

Education expands on this foundation, helping children to relate their geometric intuitions to their developing number systems and leading them gradually to an understanding of real numbers and other sophisticated mathematical entities. Generalizing, Spelke offers a broad perspective on why education is required and what education accomplishes. First of all, early emerging conceptual systems although powerful up to a point are too limited in scope for the modern world. They need to be extended and revised. Second, the mediating combinatorial power of language is too promiscuous. It permits all sorts of combinations, most of which are not very useful. Formal education focuses and edits developing children's capabilities in areas that prior generations have found to be fertile.

How does all this relate to the double gap discussed earlier? The level of Spelke's analysis is very much the same as that engaged in classrooms—counting, basic operations of arithmetic, and so forth. However, the analysis plainly focuses on an explanation theory for the development of number understandings. Spelke offers one intriguing bit of practical advice, a way of leveraging youngsters' sense of cardinality to make more meaningful the symbolic rituals they are learning in early schooling. Beyond this tip, it is somewhat unclear whether the explanation theory has extensive revisionary implications for educational practice. Not that it must, to constitute a revealing explanation!

van Geert and Steenbeek (2004, 2008) present an analysis of teaching and learning from a very different direction: system dynamics. Eschewing not only neuroscience but also

any specific psychological framework, the authors model the dynamics of teaching and learning by examining a few basic variables and parameters: the ultimate level of performance desired, the learner's current performance, the current target level the teacher would like the learner to demonstrate through immediate teaching—learning activities, the learner's rate of learning, and the teacher's rate of increasing the challenge, both responsive to the gap between current target and current performance; and a couple of others.

Simple as this model seems some compelling and cautionary results emerge from simulations. Teachers might expect steady learning toward the desired level, with some students perhaps advancing too slowly to make it. The model shows that, depending on the parameters, learners can easily stall at a level well below the desired attainment, with no further learning, however, long instruction continues. Level of performance can oscillate without showing net gains over time. Level of performance can grow slowly and then show a spurt. In summary, pace of learning and even whether one gets learning at all depend not only on particulars like scaffolding and feedback but also on general dynamic properties of the teacher—learner interaction. Learning will proceed best when the teacher or other agent recognizes the systemic phenomena in play and makes real-time adjustments to create strong steady learning.

Again it is worth asking how the perspective offered by van Geert and Steenbeek illustrates the two gaps. Although neuroscience typically presents a level of explanation much finer grained than the macrophenomena of interest to educators, van Geert and Steenbeek offer a level of explanation much coarser, bundling the complexities of instructional interaction into a few critical parameters.

The results are illuminating and potentially transformative: They warn that educational practice typically is blind to fundamental aspects of the teacher—learner interaction over time. That said, they leave a considerable gap between explanation and action. A teacher seeking to leverage the system dynamics of teaching—learning in a classroom setting would need quite frequent measures of students' performance, more frequent than normally gathered, along with ways of gauging on the same scale his/her current level of aspiration for learners as expressed through teaching—learning interactions, all rendered in graphical form to track and potentially redirect the unfolding system effects. Plainly, a fully articulated action theory would have to address a swarm of practical considerations.

LET NEURONS SPEAK

The examples in the two previous sections illustrate what seems to be the general trend: Basic brain and psychological science, including systems perspectives, often do not speak that strongly or directly to the design of teaching and learning. As characterized by the double gap, they deal principally with explanation theories rather than action theories, and they often tend to address levels of explanation different from the levels at which teachers and students act. The explanation theories certainly can inform action theories, but the translation is not always simple nor does it so frequently suggest radically different practices, more commonly justifying and deepening our understanding of practices already in the repertoire. Educational science, in contrast, is more like an engineering science, out to construct action theories that ideally trace back to broad explanation theories as well as speaking fairly directly to practice.

The problem of the double gap should not be taken as an argument that neuroscience or cognitive psychology has nothing to offer the practice of teaching and learning. To focus again on neuroscience, surely it can add convergent evidence to a conversation already underway (Bruer, 1997, 2004)—as with the challenges to one of constructivism's favorite action theories, anomaly driven learning (Petitto & Dunbar, 2004). Neuroscience can provide an explanatory backdrop and suggest an organizing framework for a tool kit of action theories (Rose, 2004; Rose & Dalton, 2009). Neuroscience can offer explanations that lead to early detection of problems based on MRI, genomic analysis, or other approaches, allowing early intervention to minimize the negative impact. For instance, Wolf (Wolf, 2004; Wolf et al., 2009) and Goswami and Szucs (2004) present alternative visions of the deficits underlying dyslexia, based largely on fine-grained analysis of psychological processes but somewhat on brain studies, along with action theory connections to remedial programs. Katzir and Pare-Blagoev (2006) relate how neuroscience is beginning to speak in important ways to the challenges of dyslexia, laying out multiple conditions for the kinds of methods and questions that make such research informative.

In the long term, the greatest contribution of neuroscience to learning may depend on action theories at the neural level. Today, we do not have them. Today, even when we can explain a deficit at the neural level, we cannot get in there and rewire the system. By and large, direct physical and chemical interventions are too crude to address underlying causes. Instead, we use strong versions of standard pedagogical practices like scaffolding and feedback applied to our best analysis of the problematic processes to work around the deficits.

One can anticipate a future where advances in biotechnology lead to action theories that target the causes of deficits at the neural level . . . and even find opportunities to amplify the capacity of individuals performing normally. However, it would be odd to call such treatments as education, and anything like a "calculus pill" seems unlikely.

In summary, what is at stake here is not whether neuroscience can inform education in certain ways—of course it can—but whether neuroscience will rewrite the book

of educational practice in the new idiom of brain-based education—of course it cannot. The double gap tells us that that is not its job and not its nature. You would not want pure neuroscience governing your classroom, any more than you would want the Newtonians instead of the clockmakers designing your next grandfather clock.

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